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EFFECTS OF SHOCK PULSE VARIABLES ON SHOCK STRENGTHENING OF METALS

FINAL REPORT

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The effects of shock pulse amplitude and duration on the hardening response and substructure of Cu-8.7Ge, Cu, Mo-35Re, and Mo have been studied. By means of flyer plate experiments, very short pulse durations (<0.1μs) have been shown to given time-dependent hardening effects. These have been related to the time dependence of plastic deformation processes. In particular, the development of twins and the sequence of twin formation leads to effective strengthening by twin boundaries. Also, twins form in much shorter times than (cont'd)

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previously demonstrated. Dislocation generation rates are at least 10^{21}-$10^{22}/m^2/s$ for the shock conditions studied. Laser-induced shock pulse studies gave results in agreement with the flyer plate results. It has been concluded that the results of this work have important implications for stress-time modeling and for other effects, such as dynamic fracture, or spallation.

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EFFECTS OF SHOCK PULSE VARIABLES ON SHOCK STRENGTHENING OF METALS

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Statement of th~ Problem Studied

The purpose of this research has been to determine the effects of shock pulse variables on the microstructure and properties of shock loaded materials. Of particular interest has been the response of materials to extremely short duration shock pulses, in the range 0.010 to 1.0μsec. Shock loading permits examination of materials behavior for stresses and strain rates beyond those available with conventional testing techniques, and these short durations make it possible to generate fundamental information about the time dependence of plastic deformation processes. An important part of the study has been to establish this time dependence for materials of several types, thus providing a basis for improved computer modeling of stress-time behavior. Generally, researchers have incorrectly assumed for modeling purposes that the plastic flow rate is high enough to ignore the time dependence for shock conditions.

Summary of Results

The shock hardening of fine-grained Cu-8.7Ge as a function of shock pressure and pulse duration at room temperature has been examined in detail.[1,2] An unusual maximum in hardening found at a duration of ∿0.10μsec has been shown to result from the sequence by which deformation twins form in the alloy. The volume fraction of twinned material increases monotonically, however, the twins form initially in bundles of 3-5 twins that are only 0.5-0.6nm thick. The thickening of these twins gives rise to a loss in strength with increased pulse duration in the range 0.10

to 0.30μsec. Longer durations give rise to an increased strength through the introduction of dislocation substructures and additional twins. The twins form in times less than 10nsec, which is much faster than previously thought. Also, the dislocation generation rate has been estimated to be at least of the order of 10^{21}-10^{22}/m^2/sec.

Similar behavior was found for shocking the alloy at 166°K, although the hardening is less because of fewer twin boundaries.[3] Increasing the initial grain size gave a lower absolute hardening, but the increment in hardening was quite large.[3] Again, fewer twin boundaries were found, but with a smaller volume fraction of twins. The plastic flow lost from twinning appears to have been compensated by increased generation of dislocations.

Repeating the original room temperature experiments on Cu-8.7Ge with Cu gave the same general dependence of hardening on pulse duration, but again there was a much reduced level of hardening. In addition, there was evidence for dynamic recovery effects at long durations.[3]

Laser-induced shock pulse effects are in agreement with the plate impact results. Although the pulses introduced by laser interaction are triangular in nature leading to rapid attenuation, the technique may be of considerable advantage for short pulse duration work, particularly in multiple shocking.

Based on the results of these studies on Cu-8.7Ge and Cu, the use of short duration shock pulses as a tool to study the time dependence of plastic deformation has been detailed in a publication.[4]

A new technique for shock loading at long durations was developed in cooperation with Dynasen, Inc. The method uses a low density structural foam projectile-flyer combination in a 2.5 inch diameter gas gun. The reduced mass of the projectile makes it possible to minimize the secondary impacts and other problems commonly experienced with gas gun recovery experiments. This method, together with the exploding foil method previously developed, has now been used in connection with studies of the behavior of Mo and Mo-35Re.[5,6]

The shock hardening increment in both Mo and Mo-35Re is large, but in contrast with the behavior of Cu and Cu-8.7Ge there is no maximum in hardening at intermediate durations.[6] The hardening increases monotonically to a saturation value for durations greater than 0.1μsec. At short durations, most of the deformation is accomplished by edge dislocations, with the residual substructure consisting primarily of long straight screw dislocations. Increasing the duration leads to the formation of large numbers of twins in Mo-35Re, but many fewer twins in Mo. This establishes that the twin boundary energy, which is approximately the same for Mo and Mo-35Re, is not the only factor important in determining whether twinning takes place. In both cases the twins thicken much faster than in the fcc materials, with thicknesses approximately two orders of magnitude larger than with the fcc materials very shortly after formation. Earlier optical studies of twinning reported in the literature have been shown to overestimate the volume fraction of twins by a factor of five or more.

Empirical relationships have been developed to account for the substructural strengthening in both Mo-35Re and Mo.[6] With shocked Mo the strengthening can be predicted from the dislocation density, while for shocked Mo-35Re there are contributions from both twin boundaries and dislocations. In both cases, and with rolling of Mo-35Re, the contribution from dislocation loops has been found to be the same as that from dislocations, and further the loop density to dislocation density ratio is constant as a function of plastic strain. This is in disagreement with an earlier report.[7] As with Cu-8.7Ge, the twin boundaries contribute to the strengthening according to a Hall-Petch type relationship; however, the strength coefficient is $\sim$5% of that for grain boundaries vs. the 1% found for Cu-8.7Ge. At smaller strains the strengthening for tensile deformation and rolling in Mo-35Re can be accounted for in terms of the dislocation density. With large strains in rolling, where a cell structure begins to form, it becomes necessary to add a term of the Hall-Petch type based on the cell size. It is

therefore possible to express the strengthening in terms of the substructure with a single expression that applies for all three modes of deformation. This unified approach has important implications, particularly for large strain deformations where considerable confusion has existed.[8]

The results for the generation of dislocations as a function of pulse duration show that the generation rate passes through a maximum at very short times.[9] Estimates of the plastic strain for each duration show that the dislocation multiplication coefficients for shocking are the same as those for conventional deformation. Although the calculated dislocation velocities are high initially, they are subsonic and decrease rapidly with time. Similarly, the plastic strain rate is high at short durations and falls rapidly with increasing duration.

The average shear stresses driving the dislocations have been estimated, thus permitting the current results for Mo-35Re to be compared with stress-velocity relationships found by conventional deformation of Mo. Although the stresses are six to eight orders of magnitude larger than those from the conventional deformation studies, the velocity behavior can be accounted for by a Johnston-Gilman type expression with a larger drag stress coefficient than that for the low stress Mo data.[5,10,11] This increase in the drag coefficient can be related to both the nature of the dislocations involved in the measurement (edge and screw for Mo-35Re vs. edge for Mo) and the presence of the hydrostatic pressure.

Based on our observations we have pointed out that it is necessary with ultrahigh loading rates to consider the theoretical shear strength of a material as a time-dependent parameter.[12] This is simply because all processes of stress relaxation are time-dependent.

Based on the electron microscope observations, a mechanism for the nucleation of deformation twins in bcc materials has been developed.[13,14] The mechanism is based on the cusps, and associated dislocation dipoles, that form on screw dislocations in bcc. Once a deep cusp with an edge dipole has formed, dissociation of the edge components occurs to form three-layer twin fragments. These form at

many levels within the slip band and coalesce to form thicker twins. As an alternative to twinning, dislocation dipole loops can form from the cusps.

Finally, the results of these studies have been related to a variety of metallurgical and shock physics observations.[9] In general, we have concluded that while shock loading can lead to some unique substructural features, there is no need to invoke physically unusual concepts, such as supersonic dislocation velocities, or supercritical shear stresses, to explain the effects. Also, the time-dependent nature of plastic flow not only requires that certain stress-time modeling experiments be approached differently, but can account for some aspects of earlier stress-time experiments.[9] The implications of the results in dynamic fracture, or spallation, experiments has also been pointed out.[9]

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Presentations

"Changes in Substructure and Properties as a Function of Pulse Duration in Shock Deformed α-Cu-Ge," American Physical Society 1979 Conference on Shock Waves in Condensed Matter, Pullman, WA, June, 1979.

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